

Shallow Water Propagation

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LONG-TERM GOALS

Develop methods for deterministic and stochastic acoustic calculations in complex shallow water environments, specify their capabilities and accuracy, and apply them to understand experimental data and physical mechanisms of propagation.

OBJECTIVES

- (A) Treat propagation from narrowband and broadband sources over elastic and poro-elastic sediments, and incorporate realistic bathymetric, topographic, and geoacoustic variations.
- (B) Quantify acoustic interactions with physical features in the ocean volume and with geoacoustic components of the ocean sediment, and analyze and interpret experimental data.

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APPROACH

- (A) Develop efficient and accurate parabolic equation (PE) techniques for applications involving heterogeneous sediments. Treat range dependence and sediment layering by single scattering and coordinate rotation methods. Benchmark results using data and special-case calculations.
- (B) Construct representations for ocean environmental and geoacoustic variability using data and parametric models. Perform acoustic field calculations with PE, normal mode, and approximation methods. Use experimental data and computational results to assess propagation mechanisms.
 - Principal collaborators are: Rensselaer graduate students and recent graduates; Dr. Michael Collins (NRL) for model development; and Dr. William Carey (BU), Dr. Allan Pierce (BU), Dr. James Lynch (WHOI), and Dr. Timothy Duda (WHOI) for theoretical interpretations and data analysis.

WORK COMPLETED

- (A) The first propagation method that combines a single scattering approximation with a coordinate rotation technique provides a major new capability [1] for accurately and efficiently handling ocean seismo-acoustic problems with range-dependent bathymetry and variable thickness sediment layers. An extension is developed for elastic media with topographic variations as in beach, island, and coastal problems [2], for which Scholte interface waves can evolve into Rayleigh waves. This PE method has improved accuracy over others, as demonstrated by applications [3] to high fidelity data from propagation over an elastic slab with variable bottom slopes in a large NRL tank. The accuracy of the approach is verified by comparisons with benchmarks for problems with large changes in shear and compressional sound speeds and with waves on range-dependent elastic interfaces [4], and selection rules are provided for computational parameters. An additional capability is added to the method for handling range-dependent transversely isotropic elastic sediments [5] that occur in many coastal regions. The first propagation model with range-dependent capabilities for a class of transversely isotropic poro-elastic sediments [6] shows the feasibility of PE approaches. For weakly range-dependent environments, increased efficiency is obtained for parabolic equation calculations at frequencies above 1 kHz [7] by combining split-step Padé and Fourier algorithms. Vector intensity and acoustic particle velocity are calculated efficiently by PE methods [8], and additional examples provide useful information on the dependence of these fields on acoustic and environmental parameters.
- (B) In waveguides formed by nonlinear internal wave fronts, acoustic modes propagating adiabatically can interact at small incident angles with the fronts to form horizontal Lloyd mirror interference patterns [9], which are particularly interesting when the fronts are curved. In contrast, full three-dimensional propagation computations show that horizontal mode coupling may arise from two or more interacting nonlinear internal waves [10], depending on their amplitudes, orientations, and coherence lengths. For improved determination of acoustic effects from nonlinear internal waves, feature parameters are estimated from satellite SAR images [11], with accuracy tested by comparisons with ground truth data from SW06 moorings. Nonlinear frequency dependence of sediment attenuation has important effects that can be physically interpreted by using a parametric description for a Pekeris waveguide to develop formulas for modal attenuation coefficients and to examine their frequency behavior [12]. Such sediment attenuation behavior is necessary [13] for

good agreement between data at the New Jersey AGS location and broadband intensity variations calculated by accounting for geoacoustic uncertainties. Attenuation coefficients obtained from a normal mode approach agree well with previous estimates found from Gulf of Mexico data [14], by identifying and employing an appropriate subset of measured sound speed profiles. Nonlinear frequency dependence of sediment attenuation and downward refraction of water sound speed profiles can combine to produce significant sensitivity in the frequency dependence of modal attenuation coefficients [15]. Expressions for modal attenuation coefficients are examined [16] using new modal approximations in order to show the influence of sound speed gradients at different locations in the water column. These modal approximations are convenient for applications because they are developed from two asymptotic approaches [17] that are valid for complementary regimes of parameter values. Connections between the frequency dependence of modal attenuation coefficients and the attenuation of averaged reduced transmission loss are quantified [18] by showing the primary dependence on features of the water sound speed profile. Efficient methods to establish relationships between the frequency power law of intrinsic attenuation, modal attenuation coefficients, and averaged transmission loss are demonstrated for several recent experimental environments [19], to assess the robustness of previous power law estimates.

RESULTS (from two selected investigations)

- (A) Ocean acoustic data analysis and other applications require capabilities for accurate and efficient propagation calculations in shallow water waveguides involving range-dependent elastic sediments and interfaces. Sediment elasticity is important because energy transfer between compressional and shear modes may significantly modify acoustic intensity and phase. In addition, handling elasticity effectively is essential in order to begin treating poro-elastic and other complex sediments. A key physical and computational difficulty is that the energy spectrum is much broader in wave number space than for fluid sediments. Our latest PE method [1] evolved from a series of steps: formulating with non-standard dependent variables; applying coordinate rotations at ranges of bathymetry slope changes; using single scattering corrections at stair step approximations of changes in sediment interfaces and volume parameters; and incorporating a procedure to reduce large changes at stair steps by introducing artificial interfaces (“slices”) as needed. The capabilities of the method continue to increase, for example by accommodating both topography and stratigraphy in beach, island, and coastal environments [2]. Benchmarking provides critical validation throughout the development, including detailed application to high quality data obtained from an experimental test series using elastic slabs in an NRL tank [3]. *Figure 1* illustrates the efficient treatment of elastic interfaces with large changes in elastic properties. The upper panel shows compressional energy at 25 Hz propagating in a sloping elastic waveguide between two elastic layers. The ratio of densities of the upper layer and the waveguide is a very small value that corresponds to the density ratio between air and water. A Rayleigh-like wave with relatively short horizontal wavelength is shown propagating along the upper interface. The middle panel shows excellent agreement between results from a range-dependent PE calculation using 8 (or more) slices at interface steps and a benchmark solution obtained from solving the corresponding non-sloping range-independent problem. The lower panel shows inaccuracies between solutions from the benchmark and from calculations using fewer slices, which illustrates the advantage of slices for elastic interfaces with large parameter changes. We conclude from these and other results that our new propagation method provides essential capabilities for efficient and accurate calculations in waveguides with range variations in bathymetry, topography, and elastic sediment structure and layering.

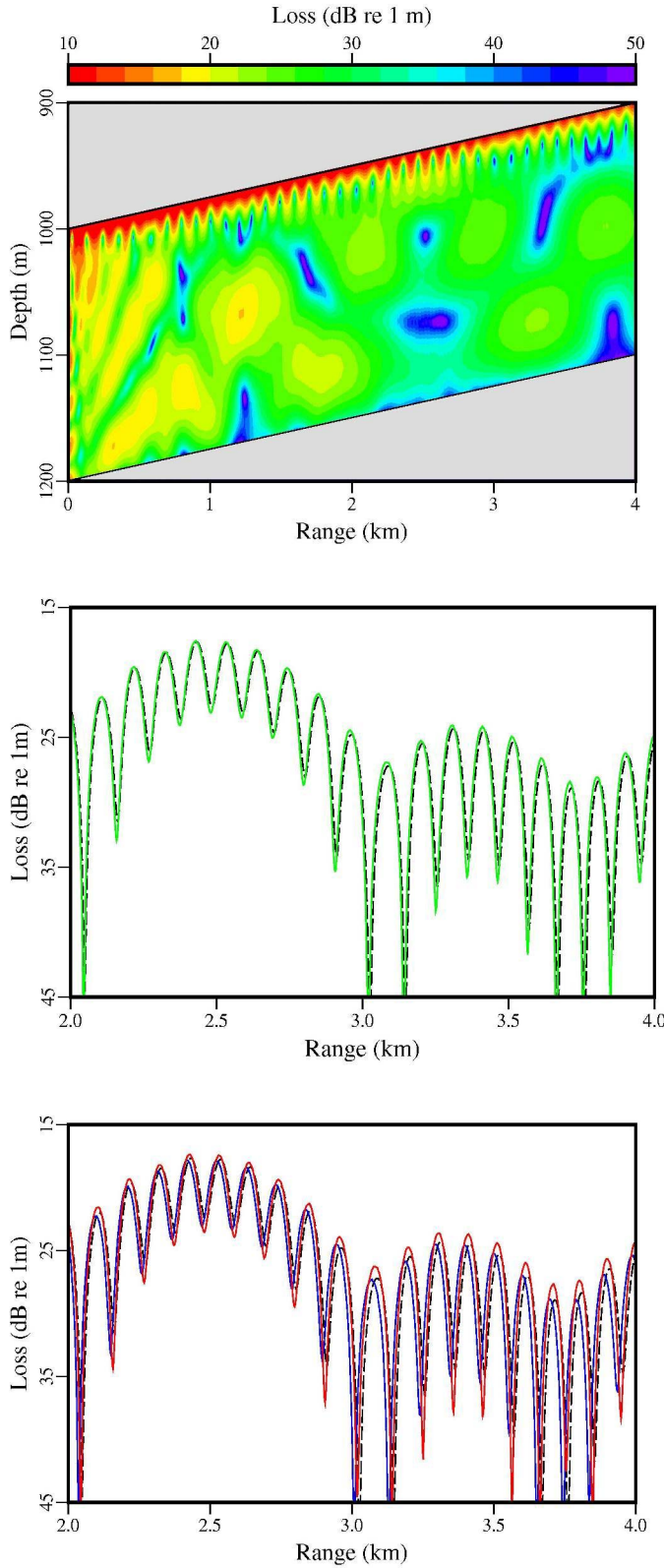


Figure 1. Accurate modeling of range-dependent interface waves is obtained from the single scattering parabolic equation. **Upper panel:** An elastic waveguide of 200 m thickness with an upward slope 1.43° is sandwiched between two thick elastic layers. The density ratio between the top layer and the waveguide is 0.001, corresponding to the air-water change. The waveguide has $c_p = 1600$ m/s, $c_s = 800$ m/s, and $\rho = 1.5$ gm/cm³, and the bottom layer values are 2400 m/s, 1200 m/s, and 1.7 gm/cm³. A 25 Hz source is placed in the waveguide 20 m below the upper interface. Color contours in the waveguide show reduced transmission loss between 10 and 50 dB (re: 1 m) over 4 km in range. A Rayleigh-like wave is visible near the upper interface. **Middle panel:** Corresponding reduced transmission loss curves on a track 10 m below the upper interface. The dashed curve represents a benchmark solution, and the green solution is calculated by the range-dependent single scattering method using 8 slices. The agreement shown between 2 and 4 km is excellent, with an oscillatory pattern having wavelength near 100 m. **Lower panel:** Corresponding reduced transmission loss curves, with dashed as the benchmark and with blue and red range-dependent solutions calculated using 1 slice and 4 slices. The blue and dashed solutions have a pattern phase mismatch, while the red and dashed solutions are aligned in phase but have an amplitude mismatch up to 2 dB. For this computationally challenging problem, close agreement between the single scattering and benchmark solutions is obtained as the number of slices increases.

(B) At low frequencies in many shallow water waveguides, estimating the transmission loss (TL) and other key propagation quantities remains a critical and relevant problem. Important and widespread ocean regions have sandy-silty sediments and relatively slow bathymetric changes. When the water column horizontal variability is weak enough in such regions, the propagating waveguide modes via their attenuation coefficients control the decrease of intensity. Consequently, fundamental issues include how the attenuation coefficients depend on environmental parameters and frequency (essential for treating broadband sources), and which modes are necessary for useful TL estimates. The first question has been examined previously, and surprises arise in the dependence on frequency [15] and sound speed gradient [16] and in applications to experimental data [14]. Recent work on the second question [18], [19] shows the connections between the attenuation coefficients and range-window averaged TL reduced by cylindrical spreading. An example is shown in **Figure 2**, which displays calculations for an idealized representation of the New Jersey shelf in the vicinity of SW06. The sediment has two isospeed layers, the upper with quadratic frequency dependence of attenuation in accord with Biot theory (more realistic depth-dependent sediment profiles produce similar results). The upper panel summarizes modal attenuation coefficients for a Pekeris isospeed water model, each curve corresponding to a different mode number n , with three cases colored. The averaged reduced TL, shown by blue circles, is determined by adding contributing modes as frequency increases. The lower panel shows a strikingly different picture when the water sound speed is a downward refracting, constant gradient profile. As frequency increases, the modal attenuation coefficients first decrease to a minimum, and then increase. The band of modes that cause the overall TL increase typically shifts toward higher mode numbers. The number of the least attenuated mode increases, for example to 13 at 1 kHz. The number of modes with significant TL contributions may decrease, as in this case from 26 (modes 1-26) at 1 kHz to 21 (modes 5-25) at 1.5 kHz. We conclude from these and related calculations that for low frequencies in many downward refracting shallow ocean regions, a band of mode numbers causes the primary increase in averaged reduced transmission loss, and the least attenuated mode typically increases with frequency.

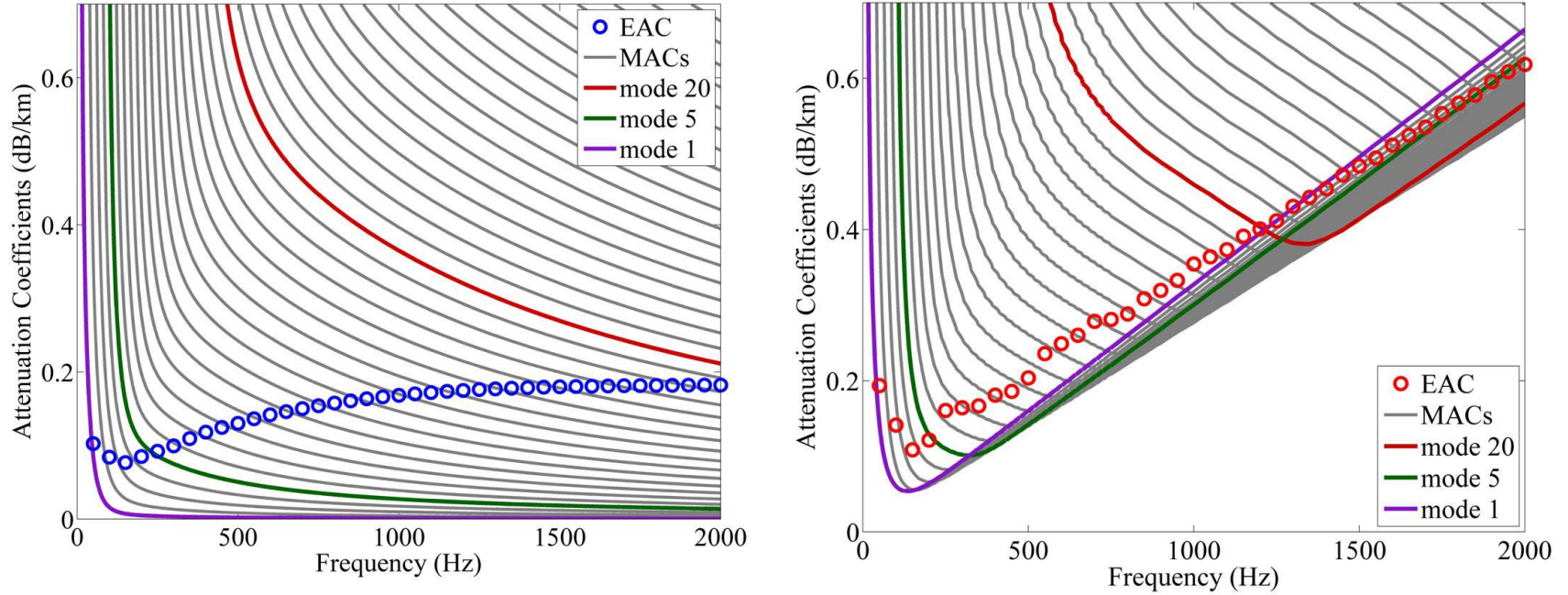


Figure 2 . *The ocean sound speed profile significantly influences the relation between modal attenuation coefficients and the overall attenuation of averaged reduced transmission loss (TL). An example is a generic New Jersey shelf environment, with water depth 73 m and a 5 m upper sandy-silt sediment layer with $c_b = 1560$ m/s and attenuation which is quadratic in frequency. A basement layer has $c_b = 1740$ m/s and attenuation which is linear in frequency. Source and receiver are mid-depth in the water, and separations up to 25 km are treated. Left panel: Baseline calculations are for isosped water with $c_w = 1483$ m/s. Portions of the modal attenuation coefficient curves between 0 and 0.7 dB/km for the first 38 modes are shown in gray, except for modes 1 (purple), 5 (green), and 20 (red), versus frequency f to 2 kHz. As f increases, all curves decrease like $1/f$, so that more modes have smaller attenuations. The averaged reduced TL is shown as blue circles at intervals of 50 Hz and increases slowly with f , nearly leveling off to 0.18 dB/km beyond 1 kHz. As f increases more modes add their contributions to the overall attenuation. Right panel: Same graphic with calculations for a linear water profile with c_w of 1528 and 1483 m/sec at the top and bottom. In this case as f increases, the curves decrease to a minimum and then increase roughly like f . The least attenuated mode has its number gradually increasing with f . The averaged reduced TL is shown as red circles, which increase with frequency on a curve like $f^{0.8}$. In downward refracting environments of this type, as f increases the band of modes that causes the overall TL increase shifts toward higher mode numbers.*

IMPACT/APPLICATIONS

New or enhanced capabilities for handling physical properties of shallow water sediments, including layering, elasticity, porosity, and anisotropy, are provided for propagation predictions. Range-dependent variability from bathymetry, topography, and sediment layer interfaces can be treated accurately in propagation calculations. Intensity attenuation and coherence statistics that result from environmental fluctuations and experimental variability can be found efficiently. Data analyses and comparisons permit specification, for experimental and application purposes, of the relative significance of key physical mechanisms: linear versus nonlinear frequency dependence of sediment attenuation, water column versus bathymetric variability, sediment heterogeneity versus homogeneity, and vertical versus horizontal mode coupling due to internal solitons and bathymetry. Results from modeling and data analyses of experiments, including several New Jersey Shelf experiments and the ACT series, are partly aimed toward improving shallow water sonar systems and predictions. New propagation model implementations, analysis tools, and data representation techniques are distributed to university, laboratory, and research and development groups.

RELATED PROJECTS

- Continuing projects with Dr. Michael Collins include completion of a monograph on state of the art advances in parabolic wave equation models and applications [20], for which principal research results are nearly complete and chapter drafts prepared.
- Research with Dr. William Carey and Dr. Allan Pierce focuses on modeling of seabed characteristics and on ocean propagation variability from the sediment geoacoustic structure and attenuation, including correlation scales and frequency dependence.
- Investigations with Dr. James Lynch, Dr. Timothy Duda, and their colleagues are directed toward the influences of water column variability, including waveguides and anti-waveguides of variable structure generated by nonlinear internal waves.

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